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Investigation of NOx and CO Formation at Ultra-Wet Conditions

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Investigation of NO_x and CO Formation at Ultra-Wet Conditions

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Chair of Fluid Dynamics
- Hermann Föttinger Institute –
Technische Universität Berlin

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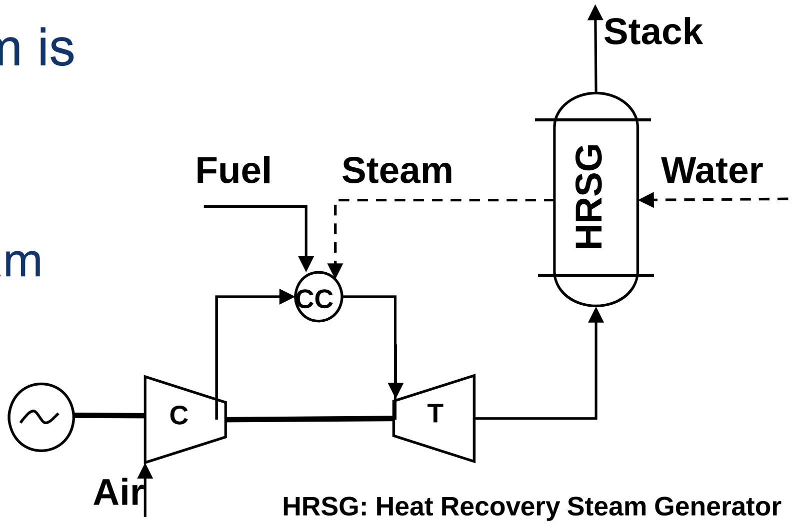
Motivation:
Humid Gas Turbine Cycle

- In humid gas turbines, water or steam is injected into the cycle
- Efficiency increase:
  - Use of exhaust heat to generate steam
  - Improved cooling
- Reduced NO_x emissions:
  - Lower flame temperature
  - Influence on chemical reactions
- Clean combustion of syngas and hydrogen



HRSG: Heat Recovery Steam Generator

- Combustion at ultra-wet conditions allows for
  - Further increased efficiency up to 55-60% in single cycle application
  - CO_2-sequestration: near-stoichiometric combustion leads to high concentration of CO_2 after condensation of the steam

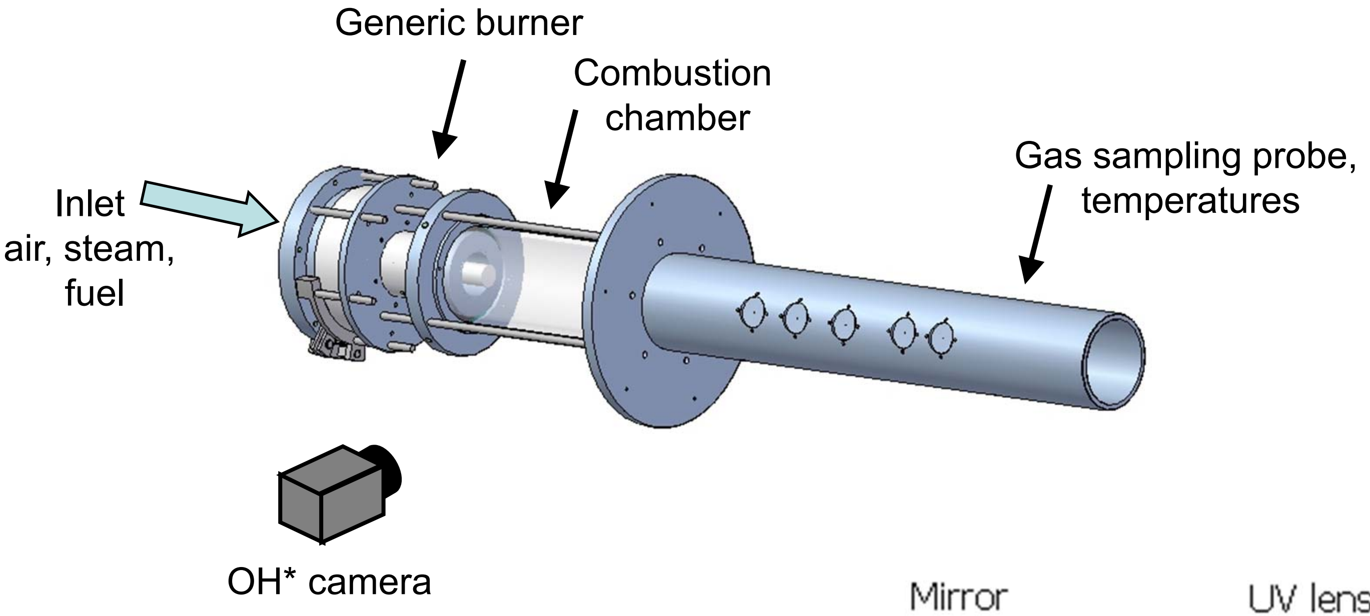
GREENEST:

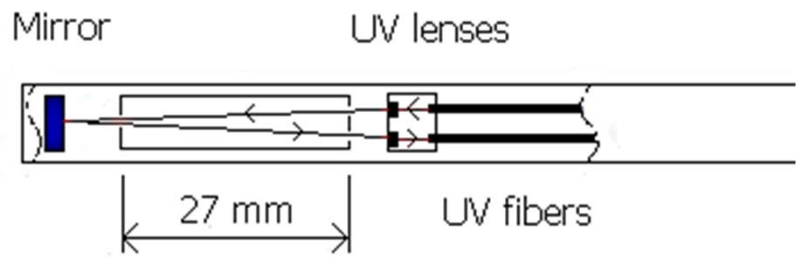
Background and objectives

- Initial assessment of atmospheric combustion at ultra-wet conditions
- Development of a modeling tool for reaction kinetics
- Influence of steam on
  - Flame shape
  - Combustion process
  - Emissions formation

- Motivation and Background
- **Experimental Setup and Results**
- Design of Reactor Network and Validation
- Results of Network Model
- Conclusions

Experimental setup:
Generic combustor

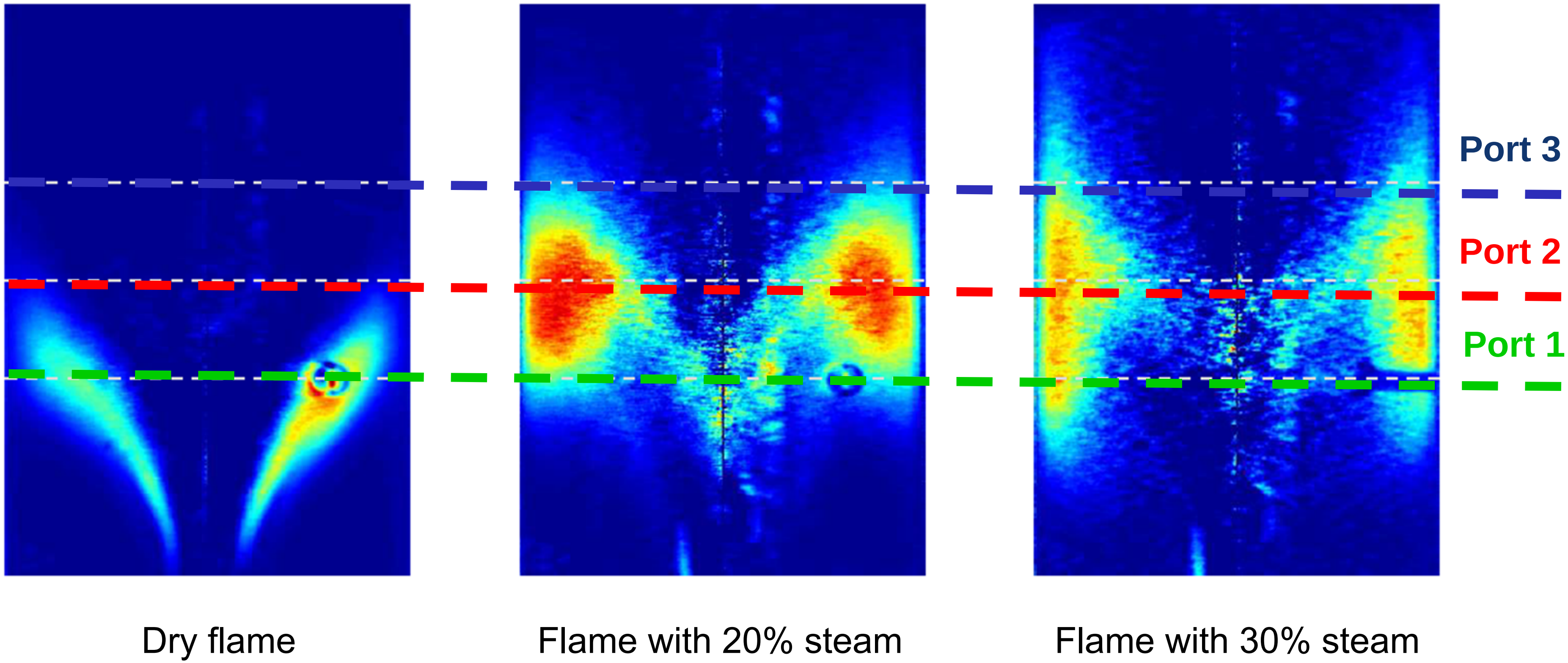




Operating conditions:

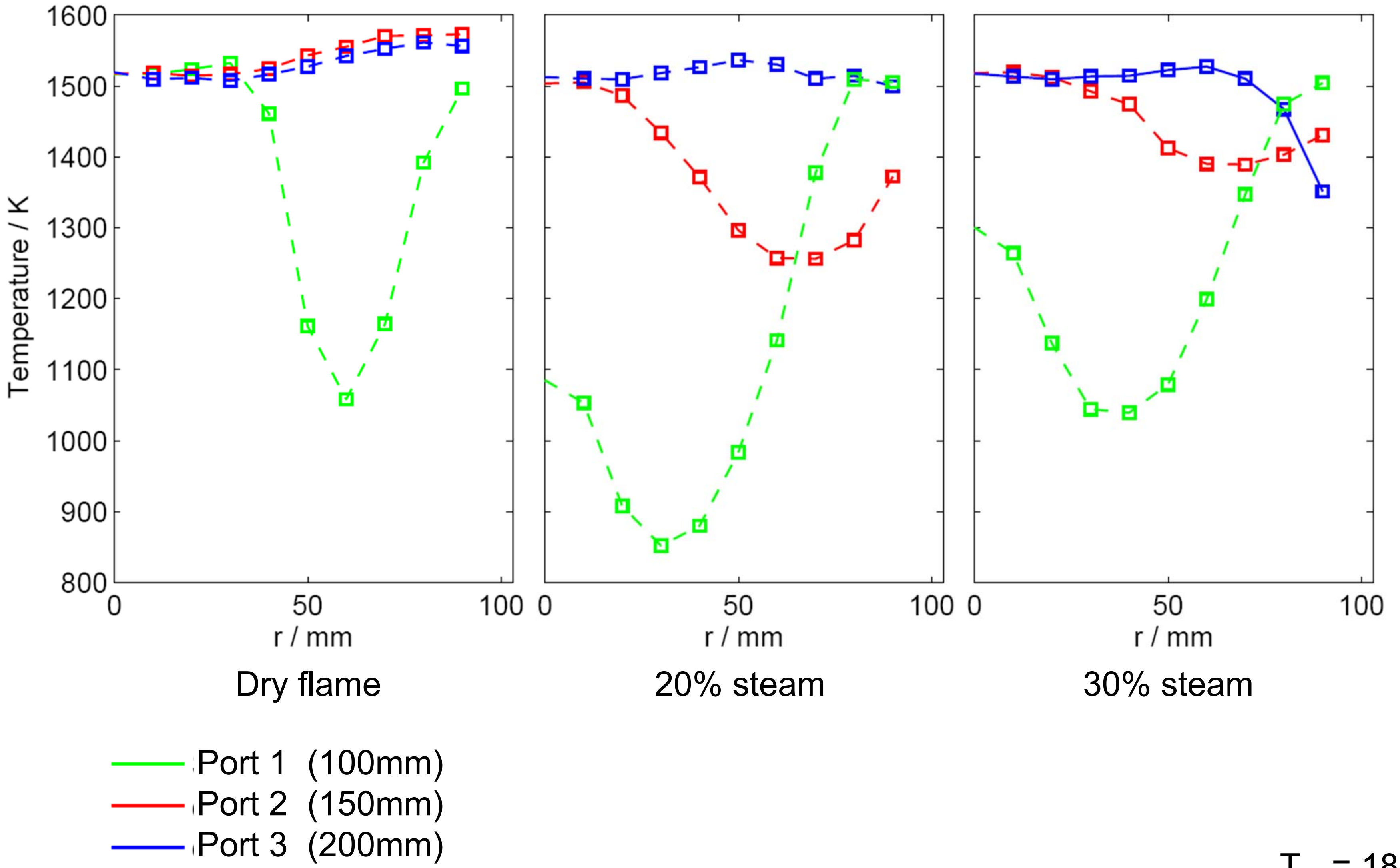
- Inlet temperature: 200°C and 370°C
- Degree of humidity:
  - $\Omega = \dot{m}_{steam}/\dot{m}_{air}$
  - Ω = 0% - 30%

OH* Chemiluminescence:
Steam increases region of heat release



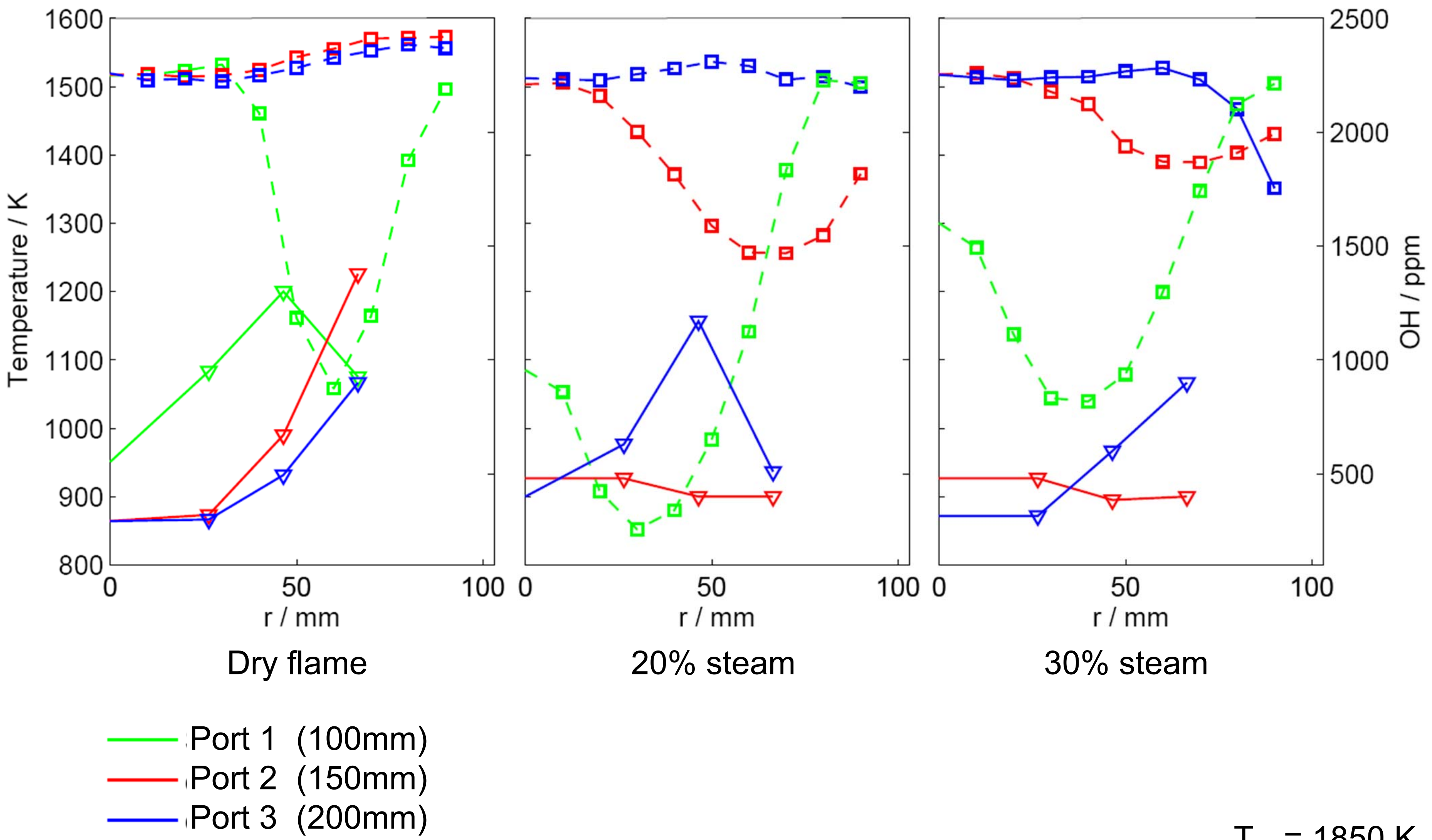
T_{ad} = 1850 K

Flame Temperature:
Flame not significantly longer



T_{ad} = 1850 K

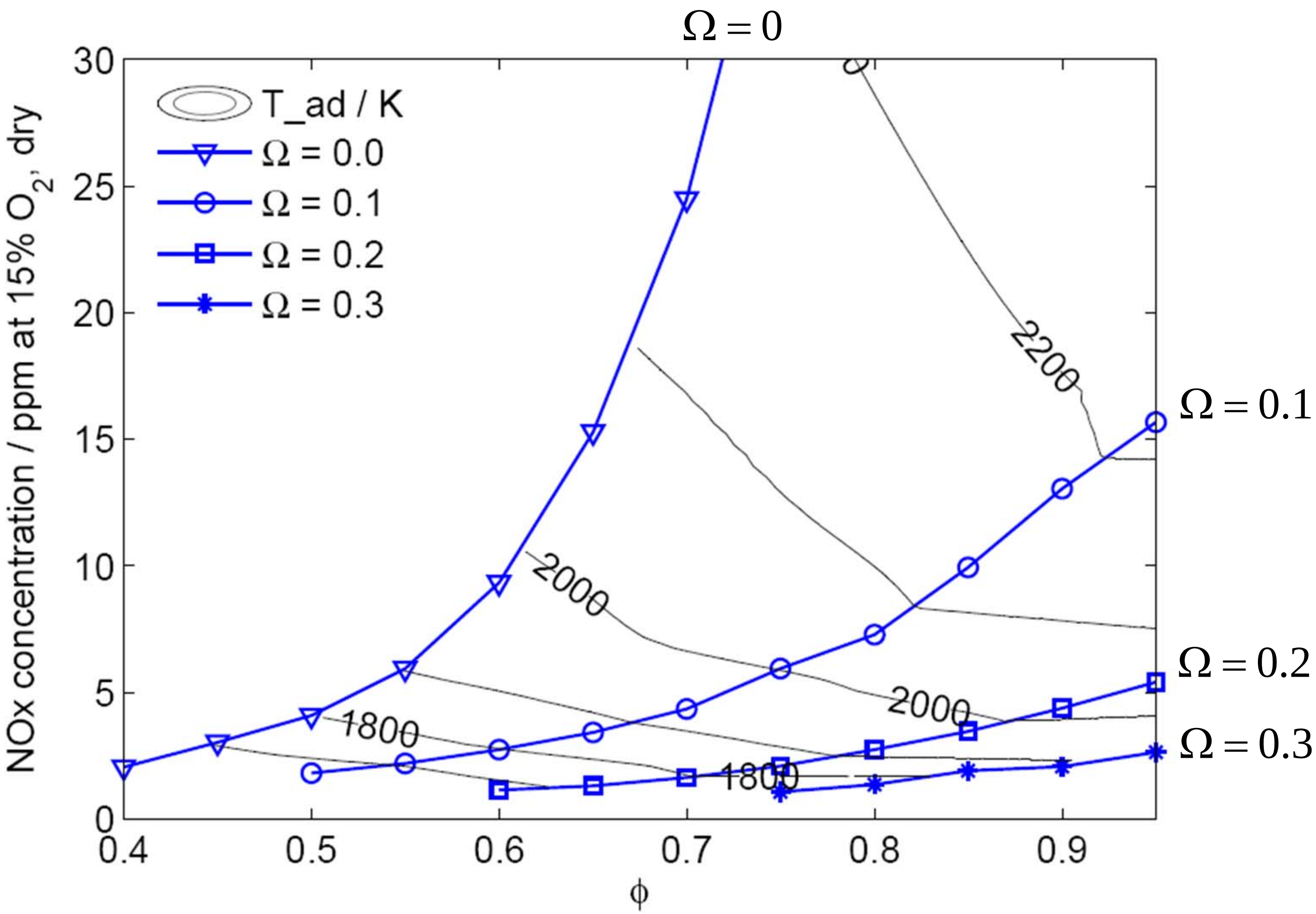
OH Radical Concentration:
Not significantly affected by steam



T_{ad} = 1850 K

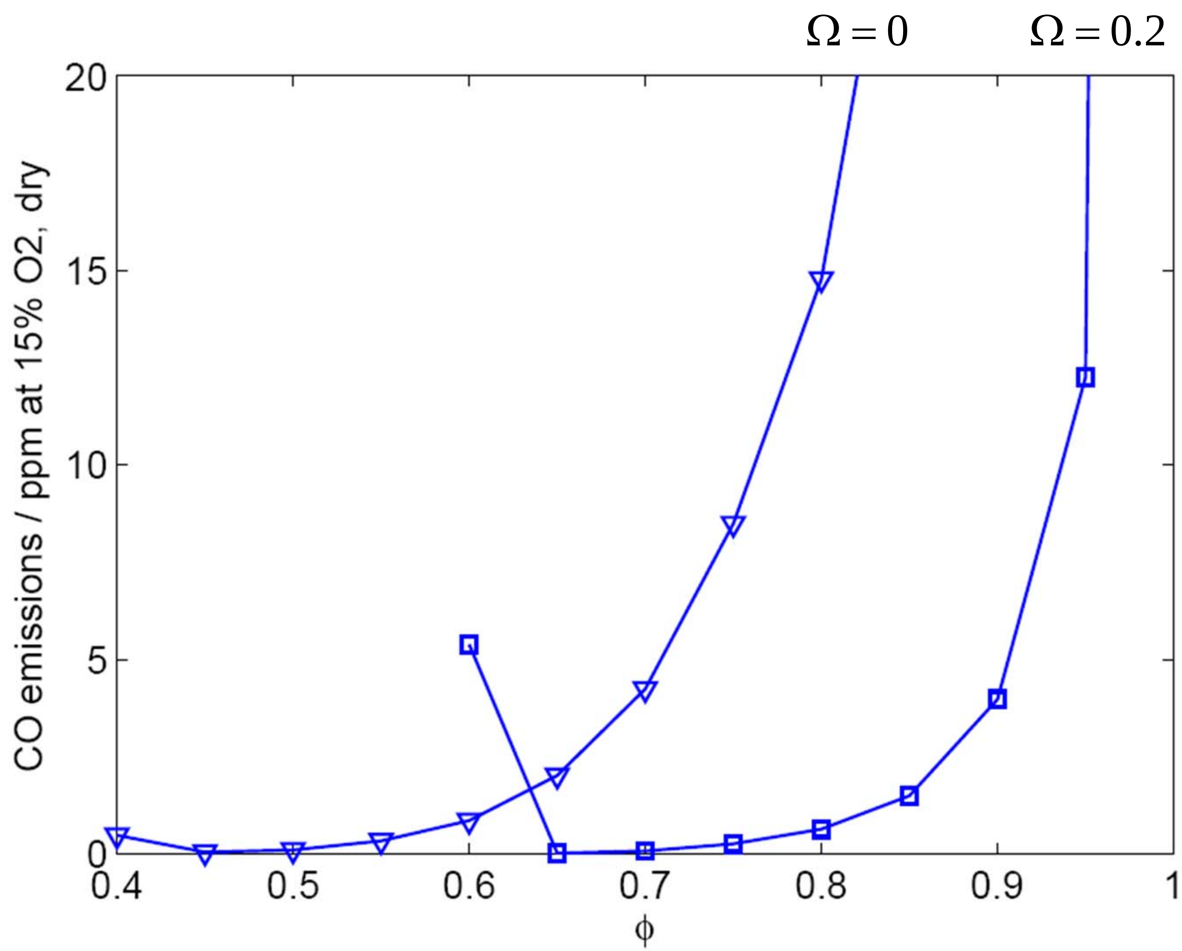
NO_x Emissions for Natural Gas:

Steam reduces NO_x even at same temperature



Measured NO_x, T_{in} = 645 K

Measured CO Emissions:
Steam does not noticeably affect CO



Measured CO, T_{in} = 645 K

- Motivation and Background
- Experimental Setup and Results
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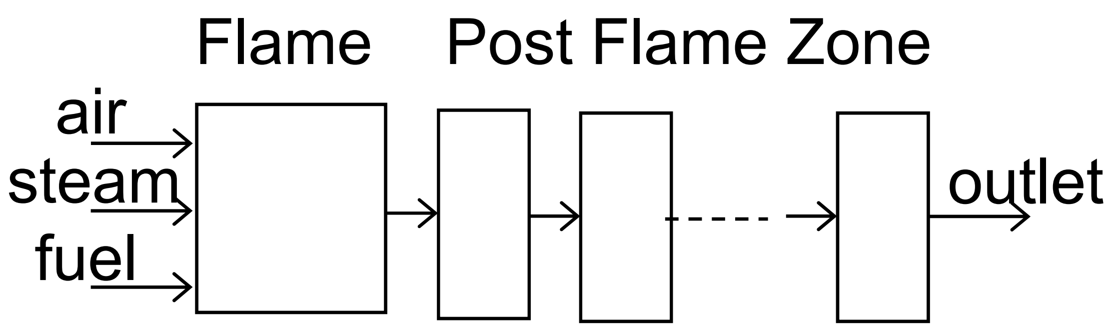
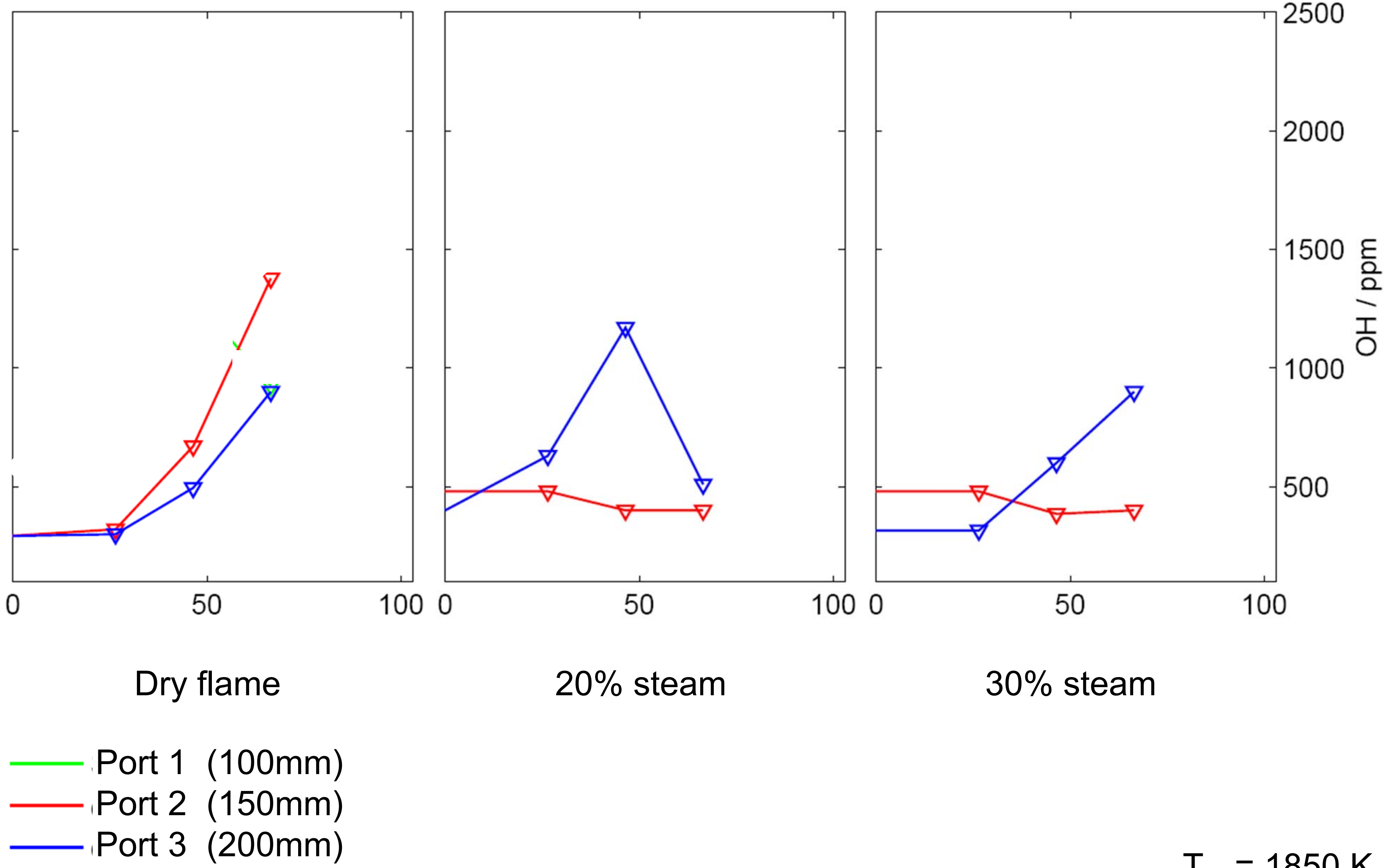
Design of Reactor Network:

Network layout

- Flame modeled by perfectly stirred reactor (PSR)
- Post flame zone modeled with a plug flow reactor (series of 20 PSRs)
- Heat loss:
  - Radiation (gray gas model and optical thin model)
  - Convective heat transfer based on measured cooling water temperature
- Reaction mechanisms:
  - GRI-Mech 3.0
  - Konnov "Reaction Mechanism for the Combustion of Small Hydrocarbons", rev 05
- Investigated operating conditions:
  - Two different fuel concentrations: X_{CH4} = 5.4% and X_{CH4} = 6.8% (Φ =0.5…0.9)
  - Three flame temperatures: T_{flame} = 1670K, 1829K, 1970K

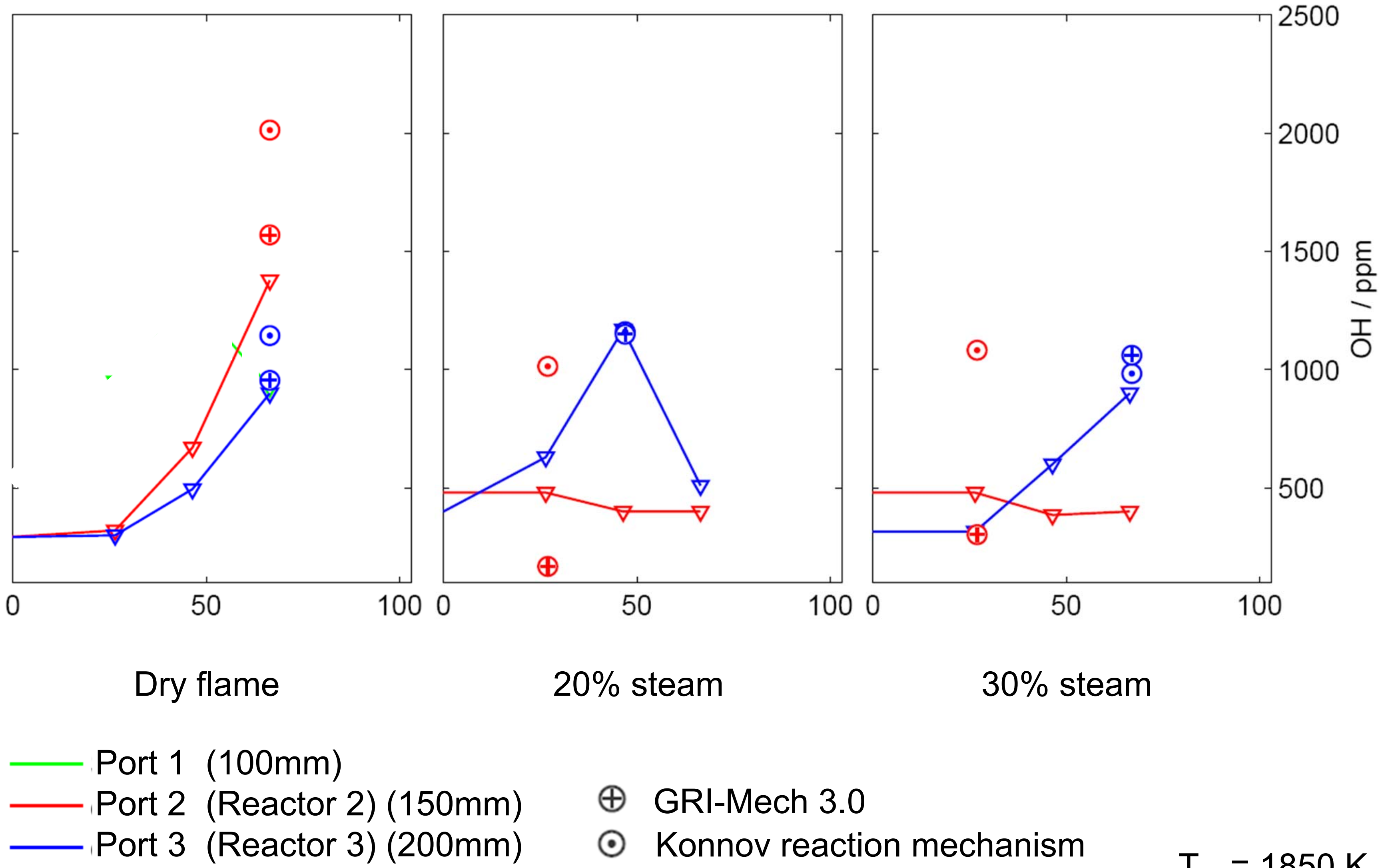


OH Radical Concentration:
Not significantly affected by steam



T_{ad} = 1850 K

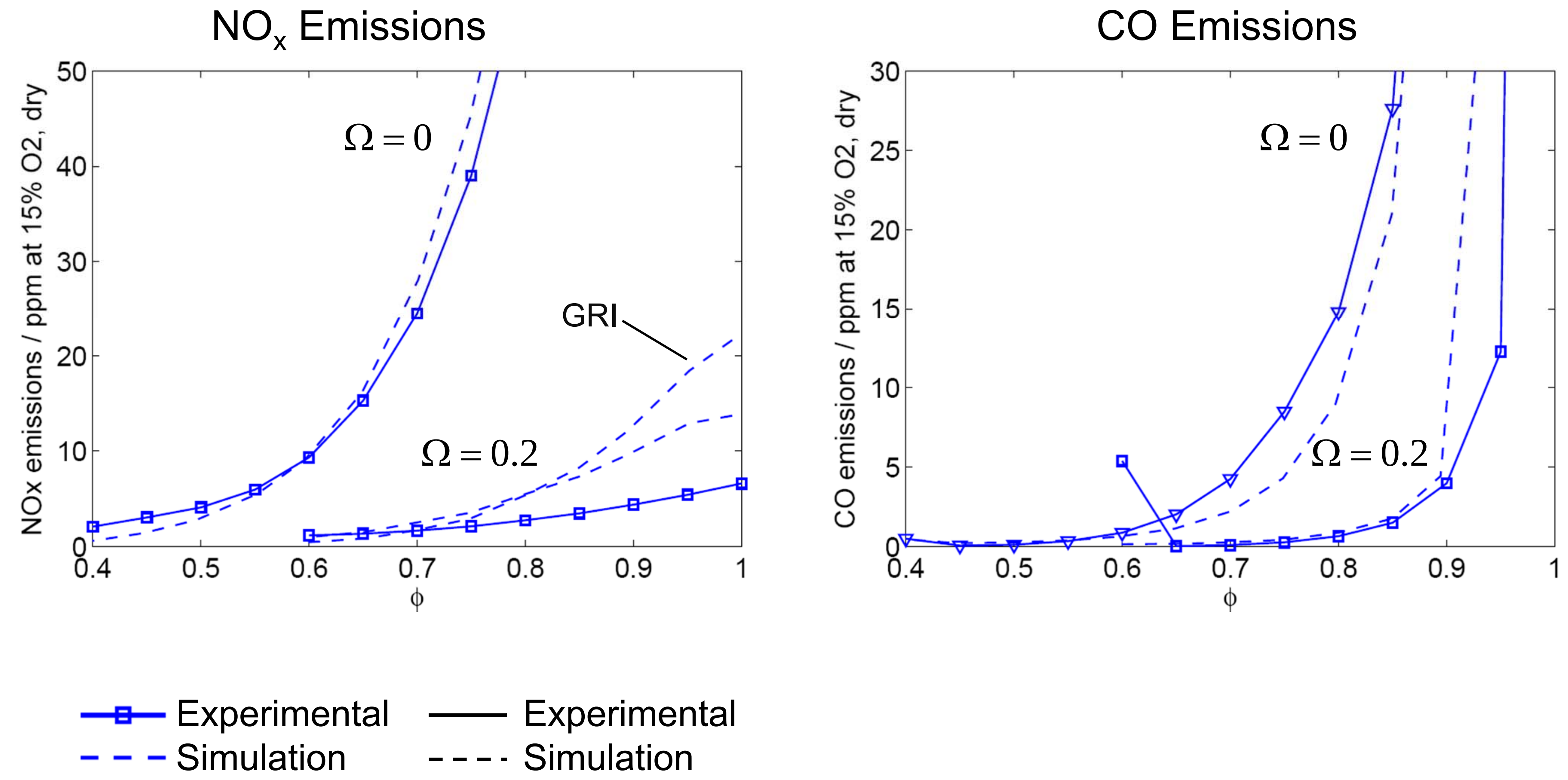
OH Radical Concentration:
Model predictions agree with experiments



T_{ad} = 1850 K

Results of Network Model:

Trends of experimental results well predicted



Measured and predicted emissions (Konnov)

- Motivation and Background
- Experimental Setup and Results
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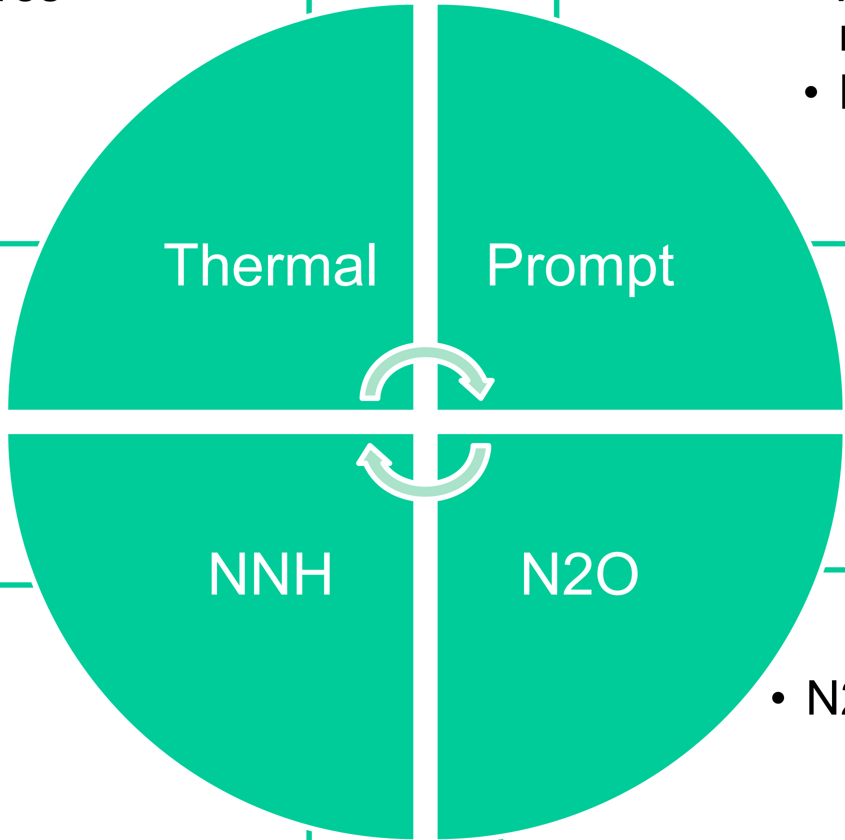
NO_x Emissions:
Formation pathways

- At high temperatures
- $N_2 + O = NO + N$

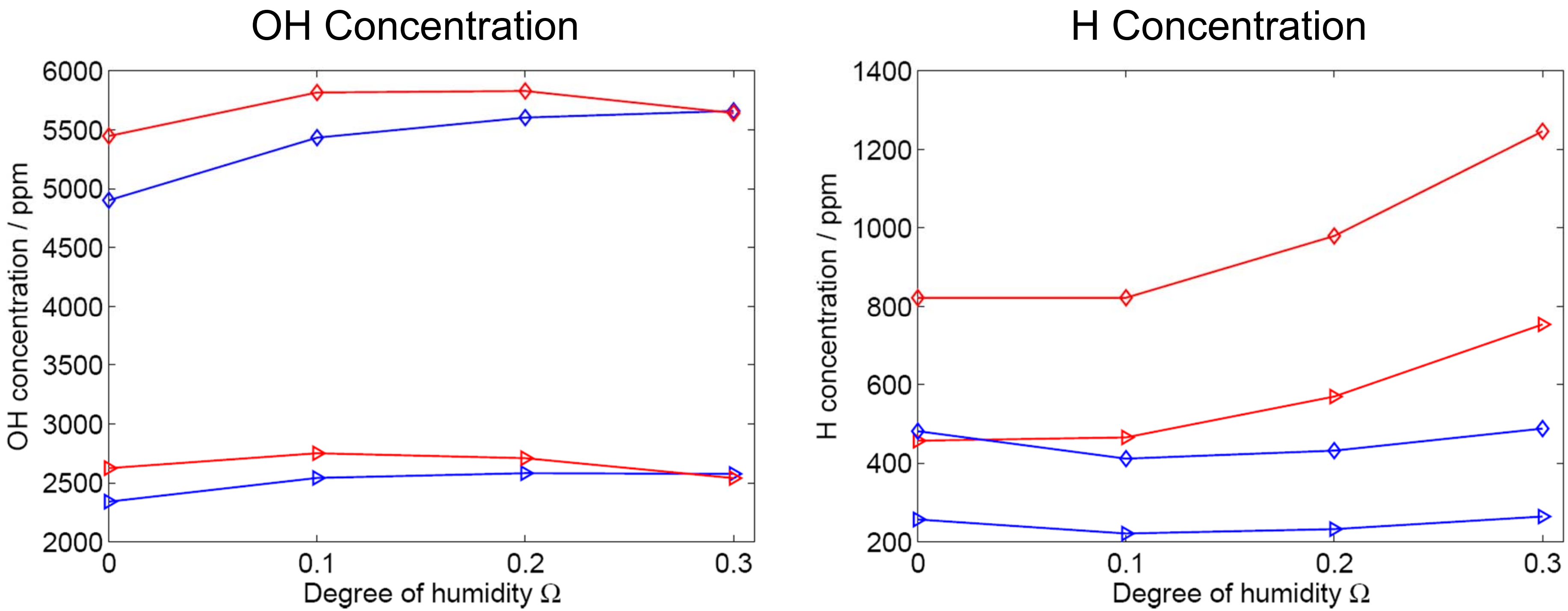
- At high equivalence ratios
- $N_2 + CH = HCN + N$



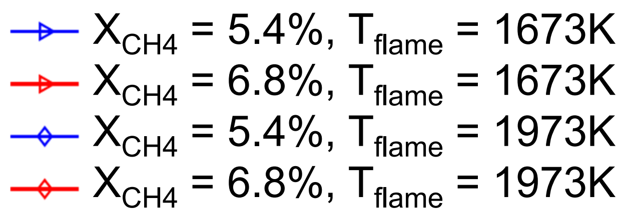
- $N_2 + H = N_2H$
- $N_2H + O = 2\ NO$

- $N_2 + O + M = N_2O + M$

Results of Network Model:
Influence of steam depends on dilution level

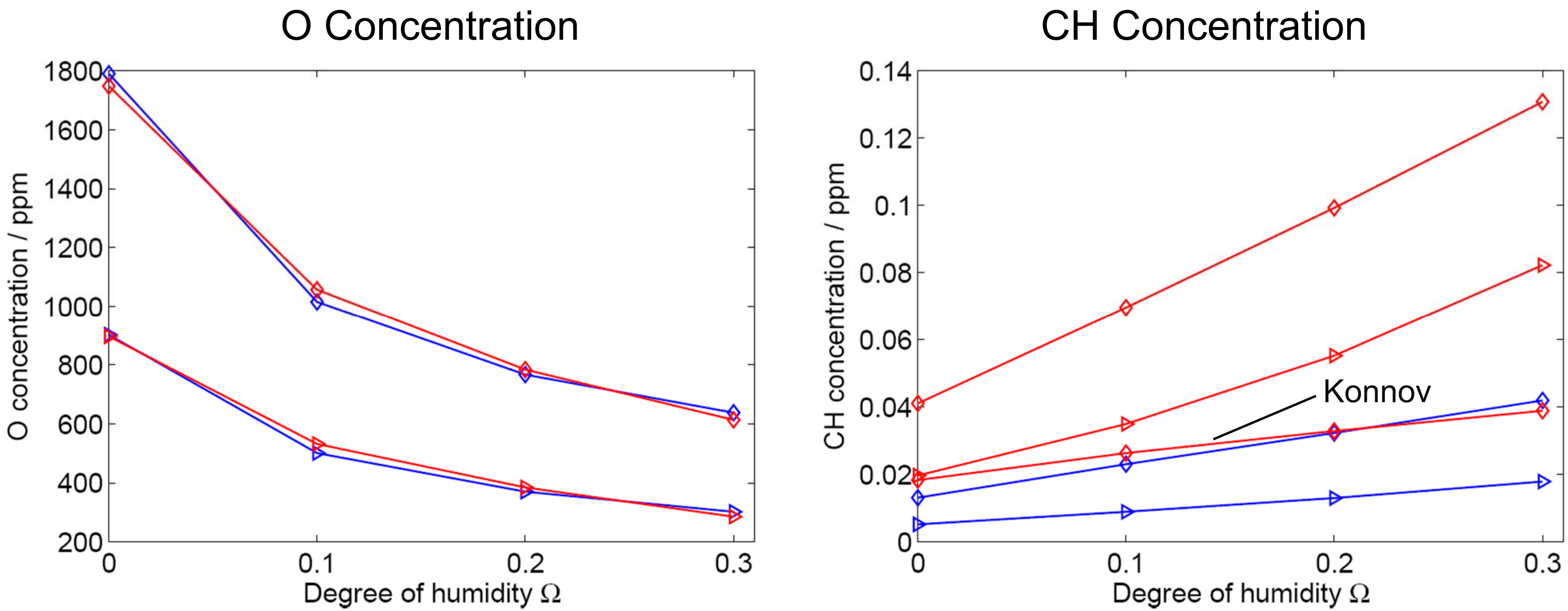


- CO formation CO + OH -> H + CO2 can be both increased and decreased at ultra-wet conditions
- NOx formation more affected by change in other species



Species concentrations in flame reactor (GRI)

Results of Network Model:
Prediction of very high CH concentrations

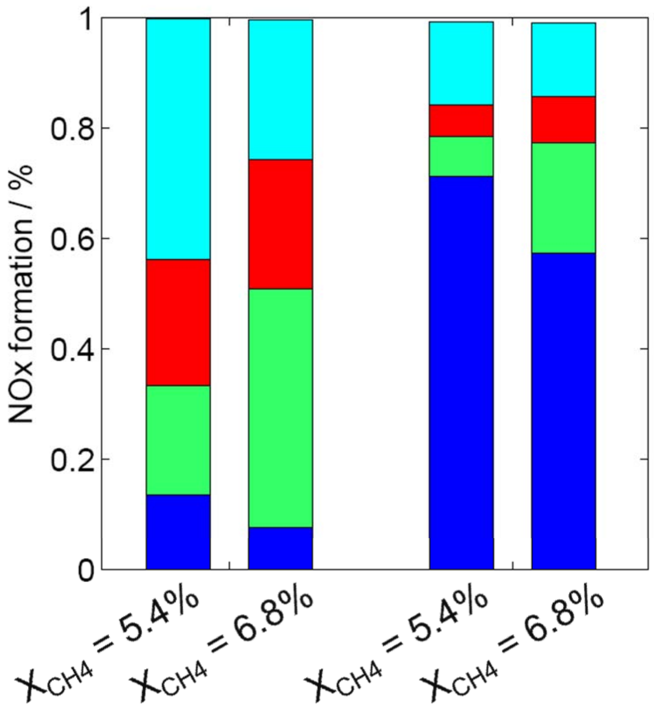


- Thermal, NNH, and N2O pathways restrained by reduced O concentration
- Prompt pathway increased due to higher CH concentration

Species concentrations in flame reactor (GRI)

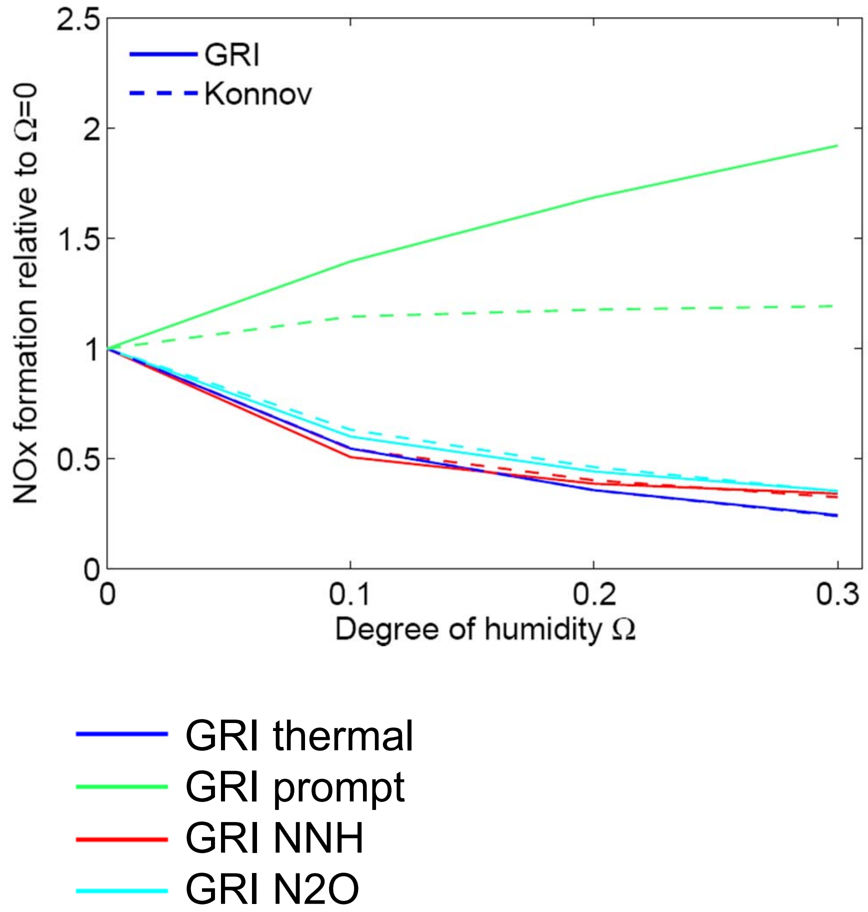
Results of Network Model:
Increase in prompt NO_x

NOx pathways at dry conditions



T_{flame} = 1670 K T_{flame} = 1970 K

NOx pathways at wet conditions



Calculated share of NO_x formation pathways

Conclusions

Experiments:

- Stable flame up to a degree of humidity of Ω = 35% for natural gas
- NO_x emissions are significantly reduced
- CO is not noticeably affected by the steam (at atmospheric conditions)

Investigation of chemistry:

- Developed model predicts the experimental results (NOx, CO, OH) well
- Influence of steam depends strongly on the degree of dilution
- Thermal NOx significantly reduced also at high temperatures
- Prompt NOx formation is predicted to increase with steam content, and might be over-predicted by the reaction mechanisms

Thank you for your attention.